Hydrogen Leading into the Future – An Industry Outlook

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Date published: August 22, 2023

Potential Hydrogen Industries and Market Sectors:

Transportation

- ***Personal/Commercial Vehicles***
- ***Heavy-Duty Trucks***
- ***Trains***
- ***Aviation***
- ***Marine Transport***

Residential/Commercial

- ***Pipelines***
- ***Fueling Stations***
- ***Heat/Distributed Power***

Industrial

- ***Refining***
- ***Chemicals and Other Fuels***
- ***Steel Manufacturing***
- ***Cement Manufacturing***

Power Generation

Hydrogen has the potential to lead the evolving worldwide low carbon energy movement. Can the hydrogen economy overcome key challenges faster and more effectively than competing low carbon alternatives and/or existing carbon resources while prioritizing and ensuring safety across all facets? This paper discusses the current industry outlook on hydrogen and highlights existing challenges for its deployment to various end users such as the transportation sector, residential and commercial buildings, and industrial facilities.

As the previous six white papers in this hydrogen series have noted, proper consideration of hydrogen standards and an understanding of damage mechanisms, dispersion, explosion, and other possible hazards are imperative to safe execution of hydrogen projects and operations. Detailed risk assessments in the forms of Facility Siting Studies (FSSs), Quantitative Risk Assessments (QRAs), and Process Hazard Analysis (PHA) can be conducted to assist facilities and other commercial enterprises in identifying possible hazard and mitigation options regarding hydrogen.

Why Hydrogen?

What makes the most abundant element in the universe such an attractive option for industry? The first paper in this series discussed hydrogen's ability to store and/or transport energy for use in a fuel cell or internal combustion engine. However, hydrogen also has applications far beyond direct use for power generation or as a fuel source.

Figure 1 provides an overview of hydrogen generation and end users currently being investigated or pursued. With increasing pressure on businesses and governments to meet net-zero energy goals,[a] hydrogen provides unique and constantly evolving opportunities to help them meet these goals.

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[a] To satisfy the Paris Agreement requirements, emissions need to be reduced by 45% by 2030 and reach net zero by 2050.

Potential Challenges to Implementing Hydrogen:

Hydrogen fuel cost

Available technology advances

- ***Efficiency improvements needed in some areas***
- ***Compatibility with existing systems***

Challenges with outfitting existing infrastructures

Storage challenges

Safety concerns due to high flammability/ reactivity

Other competing alternative energy options

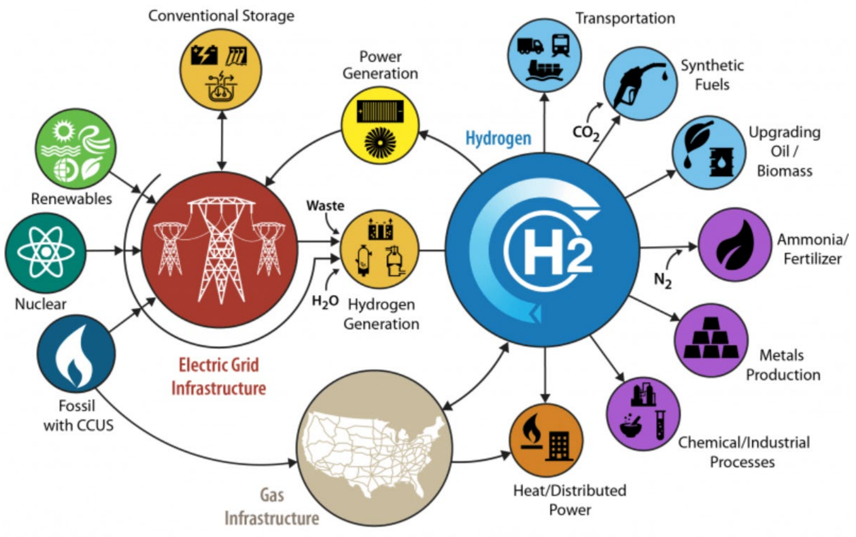


Figure 1. Potential Future Hydrogen Applications[1]

Zero carbon end users (and potential market spaces for hydrogen) represent four main sectors of the economy:

- Transportation
- Residential and commercial
- Industrial
- Power generation

This paper discusses hydrogen's outlook in each category, and key action items/recommendations to personnel and organizations pursuing projects are provided, with references to relevant topics discussed in other papers in this White Paper series on Hydrogen. While beneficial suggestions, the recommendations after each section are not inclusive of everything that should be looked at for safety in hydrogen projects and operations. It should also be noted that the hydrogen economy is ever changing, and new policies, technology improvements, and cost projections are continuously being investigated, which makes it imperative for industry leaders to stay up to date on the ever-changing status of hydrogen in various market spaces.

Transportation Uses

Several studies have been conducted to assess the potential of hydrogen in the transportation sector for personal/commercial vehicles, heavy duty trucking, trains, aviation, and shipping. As the following sections will discuss, hydrogen appears to be stronger in some areas than in others.

Personal/Commercial Vehicles

Hydrogen's greatest competitor in the personal/commercial vehicle realm is the battery electric vehicle (BEV). Both fuel cell electric vehicles (FCEVs) and BEVs are currently being heavily researched. Compared to an internal combustion engine (ICE), including a hydrogen ICE, the energy efficiency of a FCEV/BEV is not limited by the Carnot cycle, which is subject to energy losses through heat release. The potential for greater energy efficiency makes FCEVs and BEVs attractive options compared to ICEs. Currently, the potential attainable efficiency of a BEV is much higher than for a FCEV or ICE. Figure 2 compares the miles that can be driven from 1 mmBtu of natural gas based on the fuel life cycle of three technologies: ICEs/CNGVs (compressed natural gas vehicles), FCEVs, and BEVs/PEV (plug-in electric vehicles).

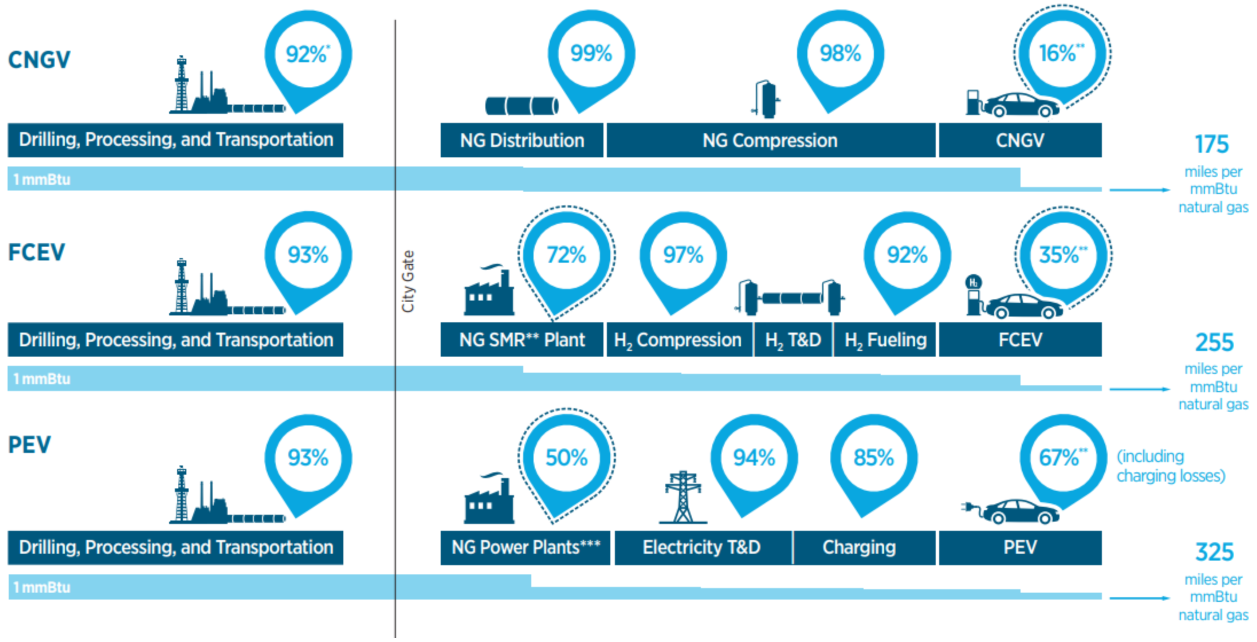


Figure 2. Example of Fuel Cell vs. Electric Vehicle Life Cycle Efficiency[2]

As the FCEV fuel life cycle continues to improve and efficiency increases, issues regarding cost, fueling station availability, and flammability hazards must be addressed. Without large-scale changes in the **personal/commercial vehicle classification, it is expected that the advantage BEVs have asserted over FCEVs will continue**.

Heavy-Duty Trucking

Within the **heavy-duty trucking classification, FCEVs are anticipated to be more competitive than BEVs in the near future.** Figure 3 provides a cost of ownership projection comparison for FCEVs, BEVs and diesel ICEs in the heavy-duty trucking classification. FCEV costs of ownership are anticipated to match those of BEVs around 2025, and the FCEVs are expected to become less expensive to operate than diesel ICEs around 2028.

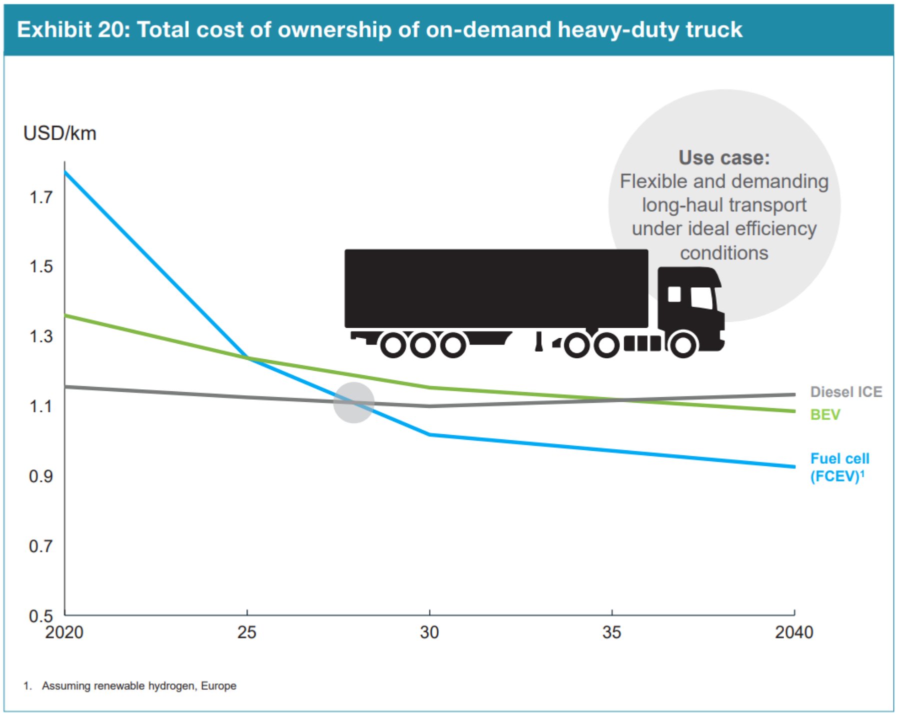


Figure 3. Cost Comparison of Heavy-Duty Trucks[3]

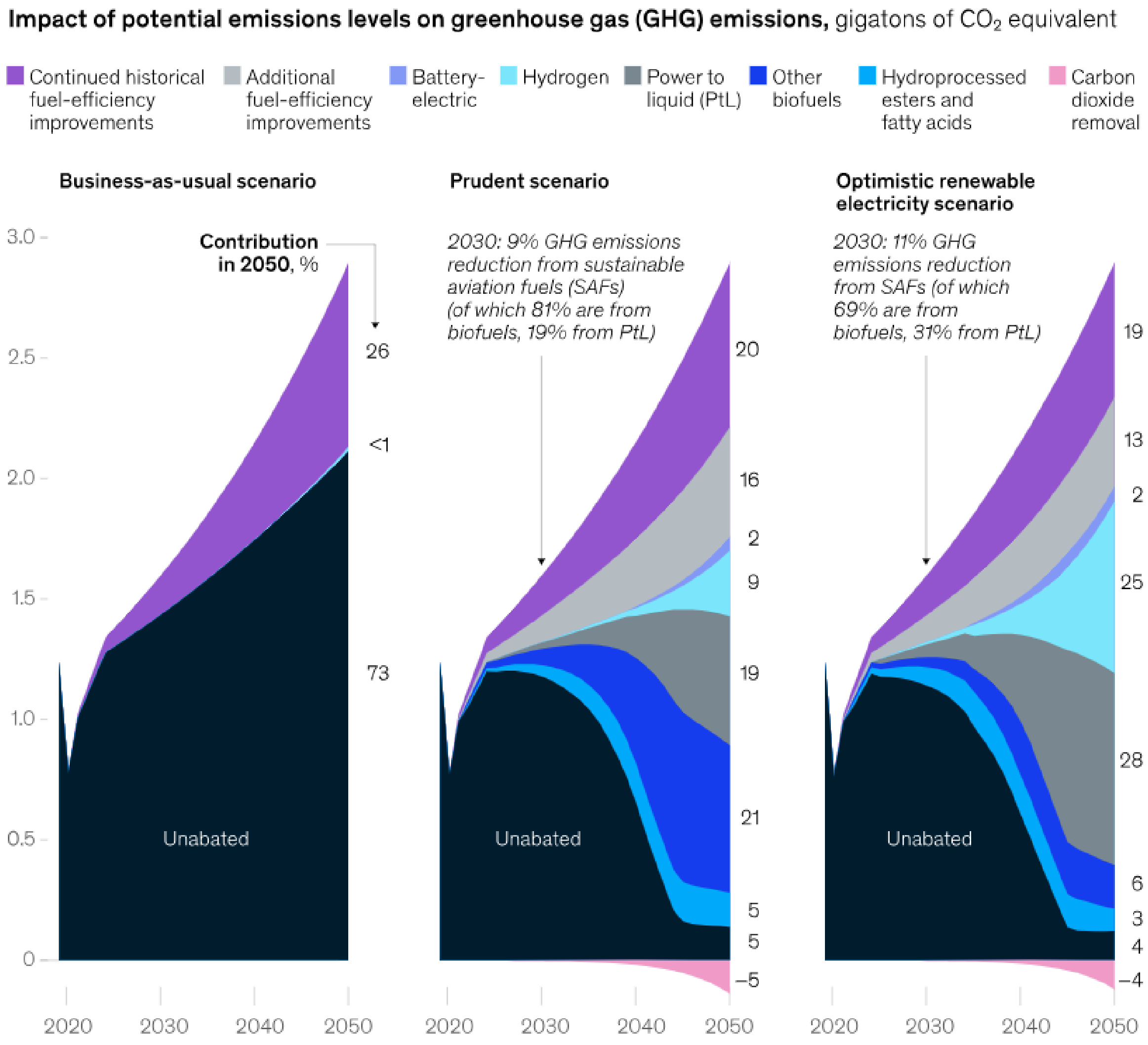
Advantages beyond cost of ownership for FCEVs in the heavy-duty trucking classification are being identified throughout industry. One study completed by Deloitte on drayage truck types highlighted the short charging time of FCEVs (5-10 minutes) compared to the 3-5 hours of charging BEVs and cited significant concerns over battery weight and range during operations.[4] The North American Council for Freight Efficiency conducted a weight study which found about 7,800 lbs of diesel components would be removed from a truck refitted with battery electric capabilities.[5] Although weight will be decreased with the removal of diesel components, the weight will need to be replaced with battery and associated equipment, which could be as high as 19,000 lbs. To achieve a longer range, the BEV will need a larger, heavier battery with a longer recharge time, so there is a tradeoff and “sweet spot” for BEVs to operate, which is likely not in the heavy-duty trucking classification. Like personal and commercial vehicles, growth of fueling station infrastructure and safety will be imperative for hydrogen’s success in this classification.

Trains

Trains are anticipated to become either directly electrified or electrified via a fuel cell (FC) as the industry moves away from ICEs. Battery electric trains have also been investigated as alternatives to ICE trains; however, there are limitations to energy density, long charging times, and battery cost/weight. **Trains powered by FCs are anticipated to be solutions where there is a high cost associated with installing and maintaining direct electrification infrastructure** (e.g., remote routes). Hydrogen-powered trains also face cost constraints, along with safety and reliability issues in this new space. Additional research and policy follow-ups were recommended as a result of the H2@Rail^{SM} workshop in 2019[6] put on by the US Department of Energy. The goal of the workshop and similar initiatives is to develop a strong understanding of safety in the use of hydrogen trains moving forward.

Aviation

Sustainable Aviation Fuel (SAF) is expected to be one of the primary competing alternatives to hydrogen in the aviation sector. An analysis projects a large portion of emission reductions coming from SAFs, as demonstrated in Figure 4. In general, there is agreement that significant technology investments and policies will need to be pursued to meet net-zero goals in the aviation sector. For hydrogen, this could mean FCs or synthetic fuels made from “clean” hydrogen. Concerns regarding increased fuel/maintenance costs, longer refueling times, and larger fuel tanks are just some of the challenges hydrogen-based aircraft will face in the commercial sector.[7] At this time, **hydrogen is projected to have a greater impact on smaller airplanes flying short distances,** as compared to larger airplanes traveling farther distances. Even with small/medium airplanes, **it is possible that the challenges mentioned above will prove to be too costly for hydrogen compared to possible battery electric alternatives.**[8]



Note: Figures may not sum to 100 because of rounding

Figure 4. Emission Reductions in Aviation[9]

Marine Transport

Several contenders are being pursued as a "clean" marine fuel, including Liquid Natural Gas (LNG), methanol, ammonia, and hydrogen. Hydrogen in an ICE requires cryogenic storage, and related high costs are associated with engine retrofits, but investigations are underway to review the potential for hydrogen FC usage by smaller vessels traveling short distances. As shown in Figure 5, it is anticipated that **by 2050 a majority of international shipping fuel demand will be satisfied by ammonia**, which may require "clean" hydrogen production. On the environmental side, ammonia NOx reductions will need to be addressed to meet International Maritime Organization (IMO) regulations (Tier 3). The toxicity of ammonia has also been raised as a safety concern; however, the International Renewable Energy Agency (IRENA) report noted that adaptation of existing safe handling practices and experience will assist with addressing the safety concern.[10] Marine transport projects would benefit from detailed risk assessments and policy developments as a result.

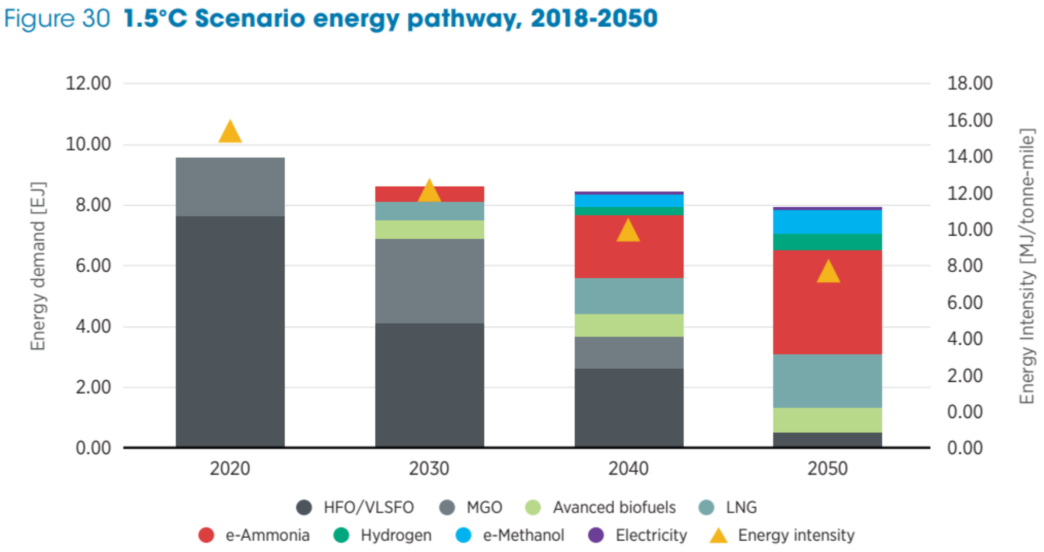


Figure 5. Possible Low Carbon Shipping Alternatives[11]

Key Recommendations for the Transportation Sector:

- Evaluate hazards and associated risk from new hydrogen operations to identify potential health, safety, and environmental impacts (discussed in Hydrogen White Paper #2).
- Perform layout/facility siting assessment for new fueling station locations to better understand potential hazards from a flammable release igniting and onsite/offsite impacts (discussed in Hydrogen White Paper #4).
- Incorporate mitigations into fueling station design to prevent hose whipping hazards (discussed in Hydrogen White Paper #5).
- Consider transportation studies to assess the hazards associated with unintended hydrogen releases during transit, particularly in confined tunnels.

Residential and Commercial Uses

The decarbonization of utility sectors as well as the usage of hydrogen fueling stations by consumers is discussed in this section.

Pipelines

The decarbonization of the natural gas grid is a challenge to unpack and one example of hydrogen's potential residential and commercial industry impact. Pipelines allow for a low-cost transportation option for hydrogen delivery and can even be used as storage reserves for excess hydrogen production. Today, several hydrogen pipelines are already active and in-use, particularly in the Gulf Coast region. Unfortunately, the majority of the United States has a much more limited hydrogen pipeline network. Compared to the common carrier routes of natural gas, hydrogen pipelines are generally under private ownership. **Repurposing parts of the existing natural gas infrastructure to hydrogen service would require significant overhaul to new components compatible with hydrogen, which is why there have been alternate discussions about blending hydrogen into the existing natural gas infrastructure.**

Most blending studies have focused on injecting 15-20% hydrogen, by volume, into the natural gas system. Pipe material compatibility with hydrogen is being extensively researched, and embrittlement of the pipes is a primary concern with increasing hydrogen volume percentages. As discussed in White Paper #3 of this series, hydrogen embrittlement results from diffusion of hydrogen atoms into steel causing pressure to the material interior. Additional research and risk studies are being performed to truly understand the potential role of hydrogen being introduced into existing natural gas pipelines.

Fueling Stations

Hydrogen's use on a residential and commercial level relies on its ability to be transported, stored, and delivered to end users. A literature-based study completed by the Nexant team analyzed several different hydrogen delivery options.[12] Figure 6 provides a cost comparison between traditional hydrogen delivery options and blended hydrogen/natural gas pipeline delivery, which would require hydrogen purification. Examples of hydrogen purification techniques include Pressure Swing Adsorbtion (PSA), membrane, and fluoronated metal hydride slurry. **The method of hydrogen delivery to a fueling station will greatly influence the type of infrastructure required at the fueling station before the final product can be dispensed to the consumer and, as a result, the cost of the fueling station itself.**

Like our current gasoline/diesel fueling stations, hydrogen fueling stations require fundamental safety systems to prevent accidental releases and ignitions that could result in fires or explosions. Hazard and risk studies along with compliance with codes and standards will be imperative as hydrogen stations are designed and operated.

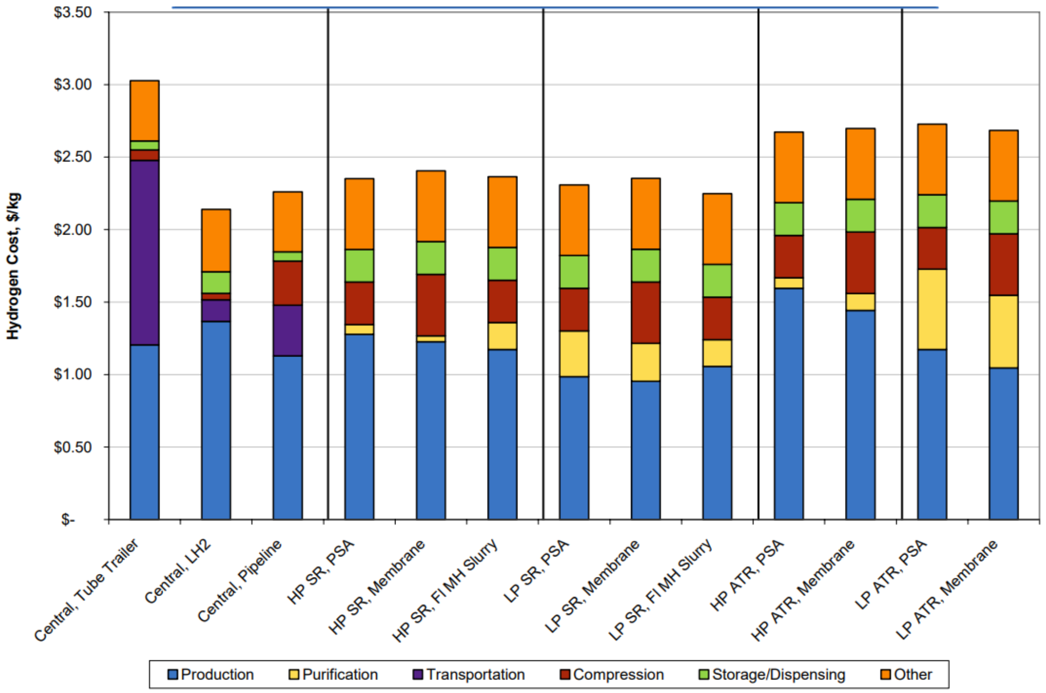


Figure 1-44 Capital Cost for Compressed Hydrogen Vehicle Fueling Station (300 vehicle/day)

Figure 6. Capital Cost Analysis for Hydrogen Fueling Stations

Heat/Distributed Power

Apart from usage in the transportation sector, FCs also have applicability in stationary systems. In many cases, stationary systems will be sized for backup power generation or heat/power. The **high reliability of FCs promotes this option to buildings that require dependable power sources in case of emergency**, e.g., hospitals, grocery stores, data centers, and police/fire stations. A wide range of FC technology options exist, with some options more prevalent due to fuel type, electrolyte/anode type, and power requirements by the end user. For instance, the Phosphoric Acid Fuel Cell (PAFC) has traditionally been used by hospitals, where there is incentive to take advantage of efficiencies by making use of the hot water byproduct of hydrogen generation. Figure 7 provides a representation of the variability in power output depending on the fuel cell technology employed.[13]

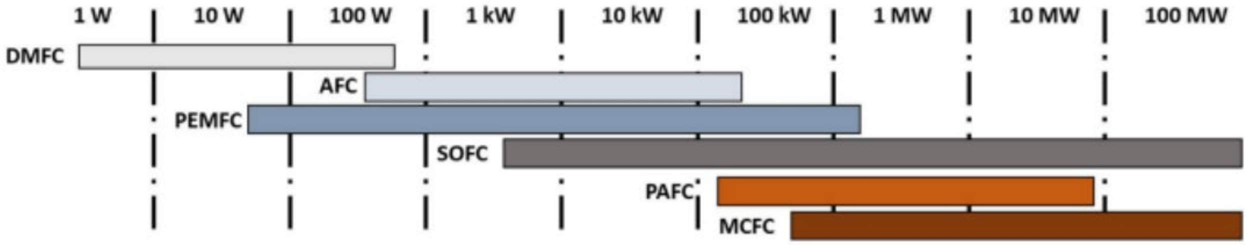


Figure 7. Fuel Cell Technology Power Application Range

Similar to personal/commercial vehicles, FCs in heat/power applications are challenged by high manufacturing costs, lack of hydrogen fuel supply infrastructure, and lack of public understanding of these systems.[14] Hydrogen FC safety is generally incorporated into the operating facility's Process Safety Management (PSM) program in the US (or a comparable safety program in another country), along with undergoing detailed PHA reviews to ensure proper safeguards and mitigations are implemented.

<u>Key Recommendations for the Residential/Commercial Sector:</u>

- Evaluate hazards and associated risk from new hydrogen operations to identify potential health, safety, and environmental impacts (discussed in Hydrogen White Paper #2).
- Design new hydrogen systems with an understanding of potential damage mechanisms and associated hazards for hydrogen production equipment (discussed in Hydrogen White Paper #3).
- Perform layout/facility siting assessment for new fueling station locations to better understand potential hazards from a flammable release igniting and onsite/offsite impacts (discussed in Hydrogen White Paper #4).
- Develop an understanding of potential Vapor Cloud Explosion (VCE) impacts or jet fire hazards to hydrogen/natural gas blends (discussed in Hydrogen White Paper #6).

Industrial

Hydrogen's industrial impact may help continue trends of growth in refining and chemicals/fuel production while also having an effect on the steel and cement industries as part of decarbonization efforts in these sectors.

Refining

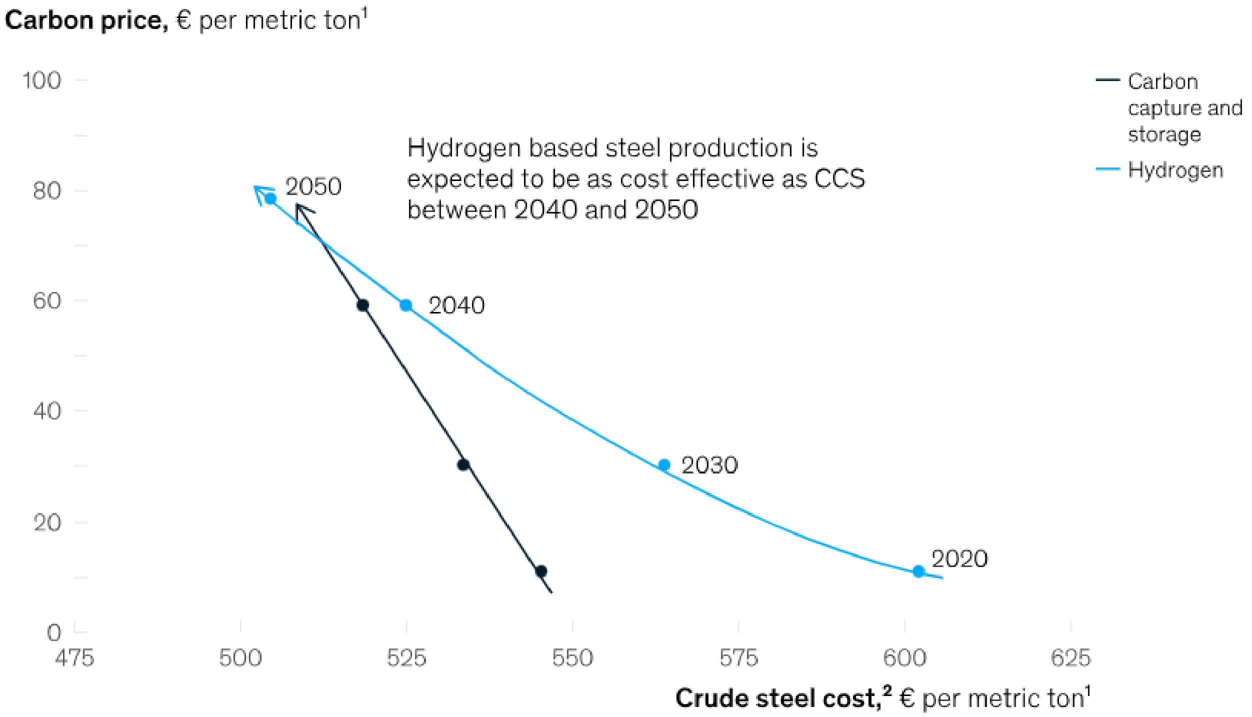
Hydrogen demand for refining purposes has been growing as global regulations continue to require low-sulfur fuels. Through hydroprocessing technologies, hydrogen is reacted with feedstock to assist with selective conversions or removals of impurities, such as sulfur and nitrogen. Generally, these processes require very high purity hydrogen to maximize the reaction efficiency and catalyst cycle. At large refineries, 15-30% of hydrogen may be produced internally by other catalytic reforming processes[15]; however, for smaller sites and for the remaining demand at the larger sites, hydrogen must be supplied externally. **"Clean" hydrogen production methods are expected to grow more prevalent with rising environmental restrictions and incentives versus traditional hydrogen production methods.** The ability of refineries to adapt their own hydrogen production facilities relies on factors including (but not limited to) land availability, hydrogen demand requirements, and accessibility/cost of "clean" hydrogen.

Chemicals and Other Fuels

Hydrogen is currently used as a main feedstock in the majority of ammonia and methanol production processes, and demand is anticipated to continue to increase over time. As with refining, the challenge to chemical processing facilities will be selecting hydrogen suppliers with net-zero carbon production options or pursuing their own "clean" hydrogen production methods. **Facilities that opt for adding a hydrogen production method to their facility will need to address hazards associated with the introduction of the new process.** As "clean" hydrogen production technologies become more advanced, it will be imperative to expand on research and policies to allow for safe, reliable operations.

Steel

The steel industry is currently estimated to contribute to roughly 6-9% of global CO_2 emissions. Carbon Capture and Sequestration (CCS) technology is one alternative that is currently being explored, alongside the use of hydrogen for the iron ore reduction step in the process.[16] Current steel production utilizes coke from coal as a reducing agent in iron production. Theoretically, hydrogen could replace the carbon source and directly reduce the iron ore to produce pure iron and water. Using hydrogen would make it possible to remove the steel industry's dependence on coal for this step, in which a majority of CO_2 emissions are generated. One of the primary drawbacks to using hydrogen for steel production, however, is the high cost required for the technology upgrades. Once the technology is enhanced, an article from McKinsey predicts that **hydrogen-based steel production will become cost-effective compared to CCS by 2050**, as shown in Figure 8.[17]



[1] 1 metric ton = 2,205 pounds.
[2] Estimated base cost is €440 per metric ton through blast furnace–basic oxygen furnace (BF–BOF) and €485 per metric ton through electric arc furnace (EAF) route at 60 percent direct reduced iron.

Figure 8. Hydrogen-Based Steel Production Vs. Carbon Capture and Storage

Cement

Cement production involves heating limestone and clay at extremely high temperatures, typically 1,450 °C, from which CO_2 is a byproduct. In addition to the CO_2 produced as a byproduct, 40% of the total emissions are due to the combustion of fuels heating the cement kiln in which the reaction is occurring. Some cement producers have funded pilot projects to investigate the use of hydrogen paired with CCS to produce high-value chemicals while reducing CO_2 emissions.[18] Hydrogen and other renewable energy sources are also being investigated for supplying some of the energy required for limestone conversion. **It is too early to assess the potential of hydrogen in this sector, as much of the technology is still undergoing extensive research**.

<u>Key Recommendations for the Industry Sector:</u>

- Conduct FSS or QRA studies to assess the impact to personnel during normal operations of hydrogen facilities that may be coming online (discussed in White Paper #4).
- Consider an update to site process safety protocol to include characteristics/impacts of hydrogen hazards that may be introduced to the site (hazards discussed in White Paper #6).
- Ensure fire water protection has sufficient supply to handle new hydrogen unit impacts.

Power Generation

Studies and projects are currently being conducted to retrofit natural gas turbines with a hydrogen supply. Another possibility for achieving net-zero carbon in the power sector is employing CCS technology on the discharge of existing natural gas turbines. The cost of hydrogen as a gas turbine fuel, however, is much higher than the cost of natural gas, which makes pure hydrogen less appealing. As with the pipeline sector, hydrogen blended with natural gas is another possibility, but the amount of CO_2 reduction would be determined by the hydrogen percentage of fuel makeup, as is demonstrated in Figure 9.[19]

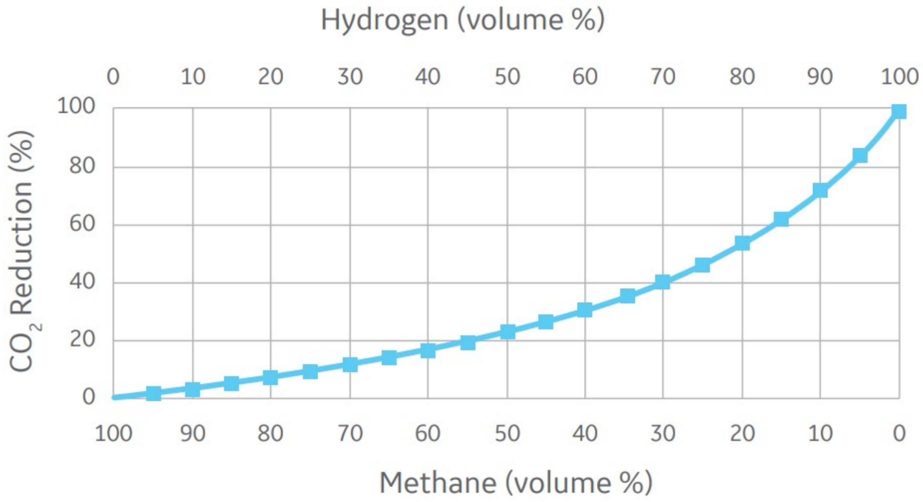


FIGURE 5: Relationship between CO_2 emissions and hydrogen/methane fuel blends (volume %)

Figure 9. Hydrogen Impacts on CO_2 Emissions for Gas Turbines

While it may help reduce or eliminate CO_2 production, hydrogen is anticipated to also increase gas turbine NO_x emissions. Research into an applicable combustor type is being conducted to limit NO_x formation, which will allow power plants to continue to meet emission regulations.[20] **Projected hydrogen fuel costs and availability are additional challenges for hydrogen integration into the power sector that are being investigated when considering hydrogen vs. CCS for gas turbine clean energy transition, although many believe both to be valuable options.**

Key Recommendations to Power Generation Sector:

- Evaluate the pipelines and equipment types for susceptibility to hydrogen embrittlement, and if applicable, consider replacing them with metallurgy more suitable (discussed in Hydrogen White Paper #3).
- Perform an updated facility siting study to ensure personnel are located in low consequence/risk areas with the presence of the highly reactive material (discussed in Hydrogen White Paper #4).

Conclusions

Understanding and safely addressing challenges discussed in this paper are imperative to hydrogen's future in the economy and the world. Educating the public properly on hydrogen safety and relative risk are central to hydrogen's acceptance in new sectors discussed in this paper. Although it is difficult to predict just how the hydrogen industry will look in 30 years, it is certain that proper risk management, research investments, technology developments, and safety communication will be integral to hydrogen's success in each market sector.

For additional information on some of the topics discussed in this white paper, please refer to the previous papers in our Hydrogen White Paper series:

Hydrogen White Paper Series:

1. **Hydrogen: The Universe's Original Energy Vector** - Reviews hydrogen properties historically, discusses some of the emerging/re-emerging technologies, and highlights the hazards associated with hydrogen and other hydrogen carriers.
2. **Hydrogen: Analyzing Its Hazards** - Reviews hazard identification techniques available to evaluate the hazards/risks associated with hydrogen systems.
3. **Hydrogen: Damage Mechanisms on Hydrogen Production Assets & Equipment** – Focuses on the materials and potential damage mechanisms and hazards associated with operation of equipment exposed to hydrogen, including pressure vessels, pipelines, piping, and other equipment handling hydrogen.
4. **Hydrogen: Facility Siting and Risk Analysis** – Discusses the importance of risk assessments and also provides an example of a hydrogen facility risk assessment, and how such an assessment can be utilized to achieve societal goals of a less carbon-intense energy infrastructure while also maintaining a safe work environment
5. **High Pressure Hydrogen Hazards** – Focuses on hazards associated with hydrogen in high-pressure applications.
6. **Hydrogen: Past and Future Test Programs** – Reviews publicly available hydrogen testing initiatives that have been performed by BakerRisk, our clients, and the Explosion Research Cooperative (ERC).

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